Hydrodynamic Instabilities on NIF

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Nuclear Astrophysics Workshop
August 27-30, 2007
Livermore, CA

Outline

- Motivation and Background
  - How can astrophysics experiments be performed at a laser facility?
- Omega Experimental Details
- Possibilities for Experiments on NIF

This work is the product of many people…

Key Participants:

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T. Plewa, R. Rosner, N. Hearn, C. Meakin, U. of Chicago

D. Arnett U. of Arizona

J. Knauer, A. Frank, T. Boehly LLE

Other Collaborators:

D. Ryutov, B. Blue, W. Hsing, S. Glenzer, M.J. Edwards, LLNL

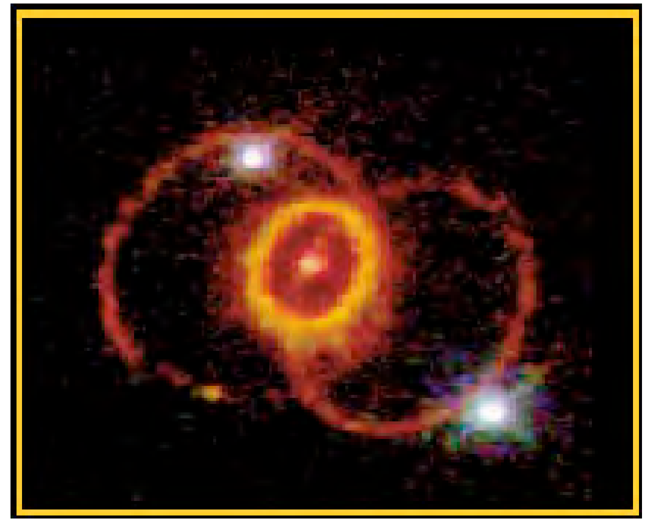
S. Bouquet, A. Casner, CEA

J. Glimm, Y. Zhang, SUNY

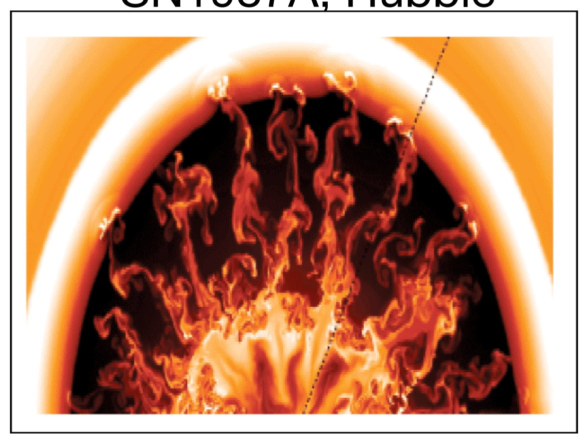
T. Ditmire, U. of Texas

Understanding SN1987A motivates supernova hydrodynamics experiments

- SN1987A
  - Core-collapse supernova (SN)
  - Early high-Z x-ray lines
  - High velocities of high-Z material
- Simulations
  - Only one* recent simulation reproduces heavy element velocities
  - 3D simulations coupling all interfaces of star not yet feasible



SN1987A, Hubble

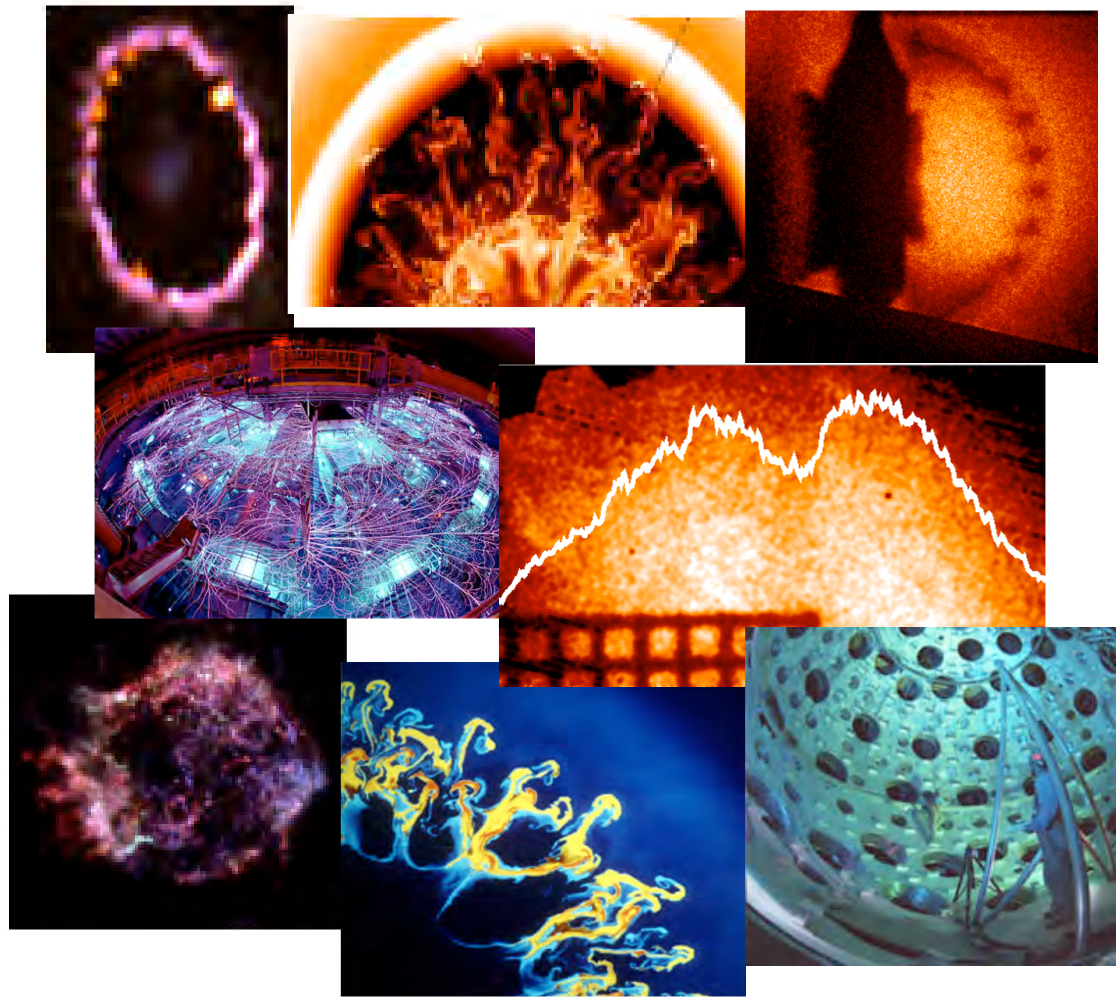


Kifonidis, 2003

*Kifonidis, et al., Astronomy and Astrophysics, 2005

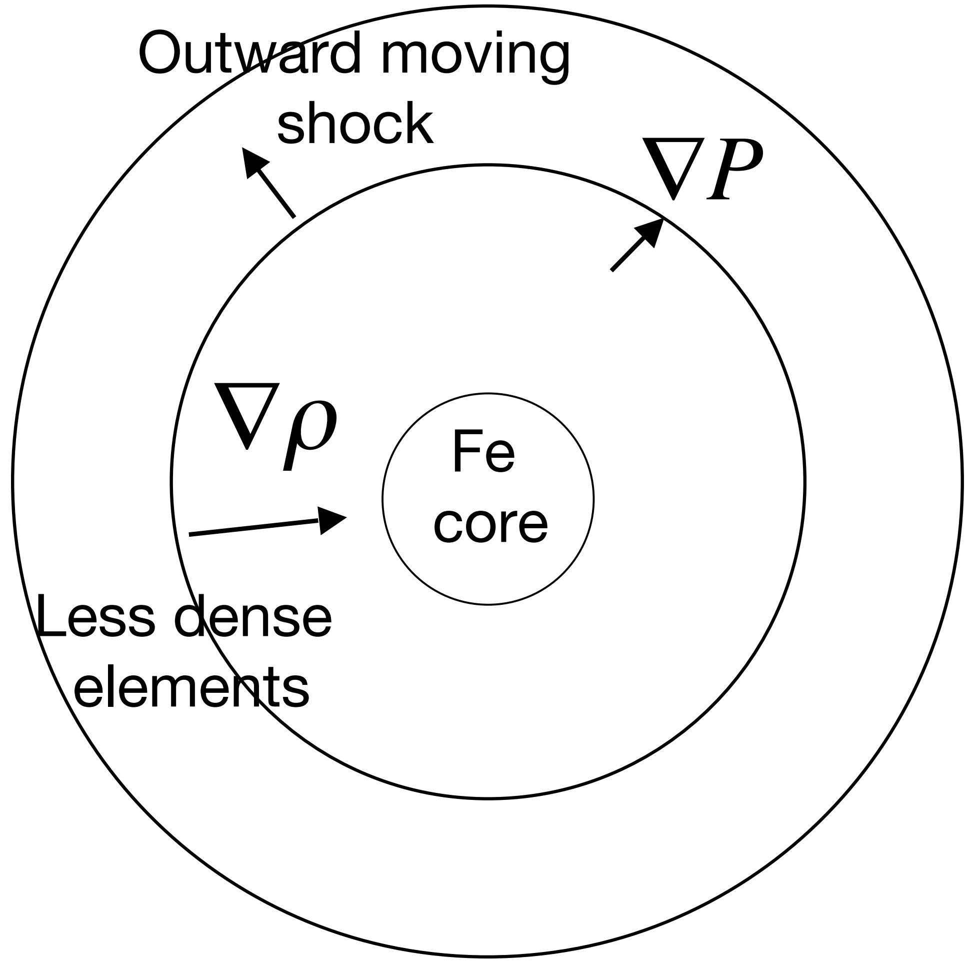
Laboratory Astrophysics links astrophysical simulations and observations

- High Energy Density Physics produces large energies in mm scale targets
  - Laser facilities
  - Z-Pinches
- Create ionized, high pressure systems
- Produce processes in the laboratory that occur in astrophysical systems
  - Sometimes in a well-scaled environment



SN1987A and hydrodynamic instabilities

- Core collapse SN
- Blast wave moving outward
- ∇P opposite direction of $\nabla \rho$
- Perturbations on surface induce hydrodynamic instabilities



Hydrodynamic fluids described by single-fluid Euler's Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) = -\nabla p$$

$$\frac{\partial p}{\partial t} - \gamma \frac{p}{\rho}\frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla p - \gamma \frac{p}{\rho} \mathbf{v} \cdot \nabla \rho = 0$$

- A good approximation for an ionized gas
- See Ryutov et al. ApJ., 518, 821 (1999)

Euler Equations are invariant under transformation

- If two systems are hydrodynamic and related by the transformation below then there is a direct correspondence between the two systems*

$$r_{SN} = a r_{lab} \qquad p_{SN} = c p_{lab}$$

$$\rho_{SN} = b \rho_{lab} \qquad t_{SN} = a\sqrt{\frac{b}{c}}\, t_{lab}$$

	SN	lab
r	10^{11} cm	10^{2} μm
ρ	10^{-2} g/cc	1 g/cc
p	10 Mbar	1 Mbar
t	1000 s	10 ns

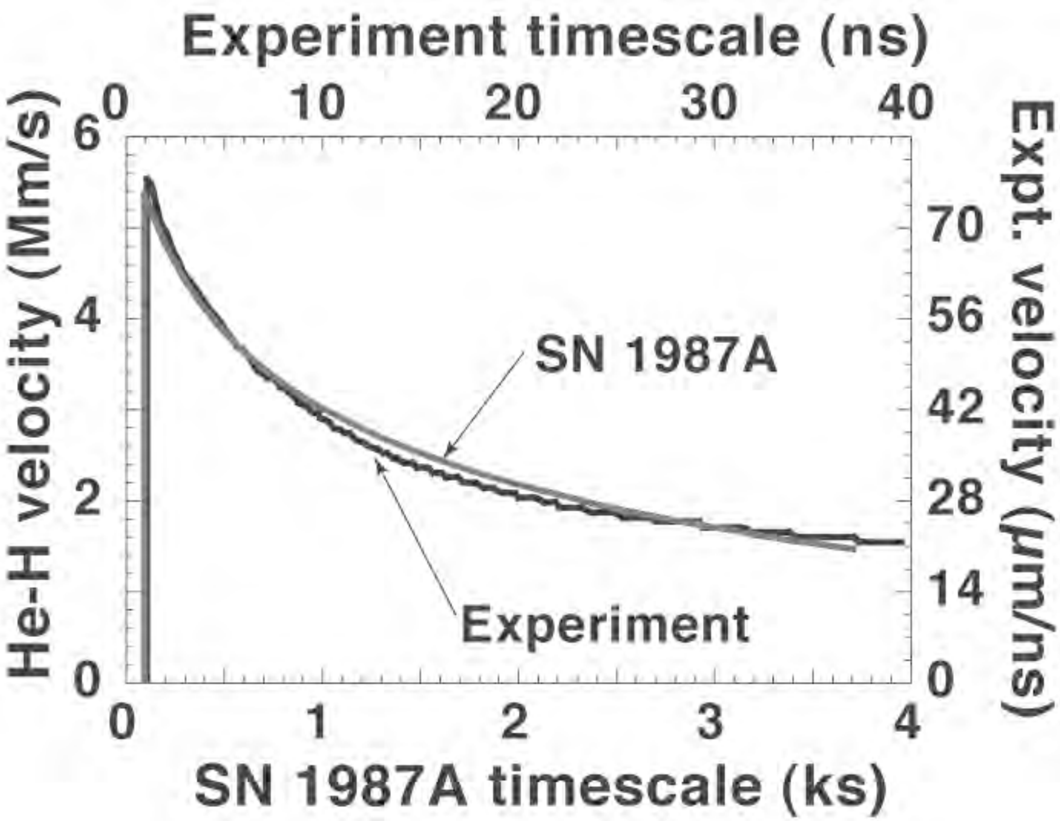
Certain conditions need to be met…

- System must be highly collisional, $\lambda_c << r$
- Viscosity negligible, Re >> 1
- Heat conduction negligible, Pe >> 1
- Radiation flux negligible, $Pe_\gamma >> 1$
- Gravitational and magnetic forces negligible

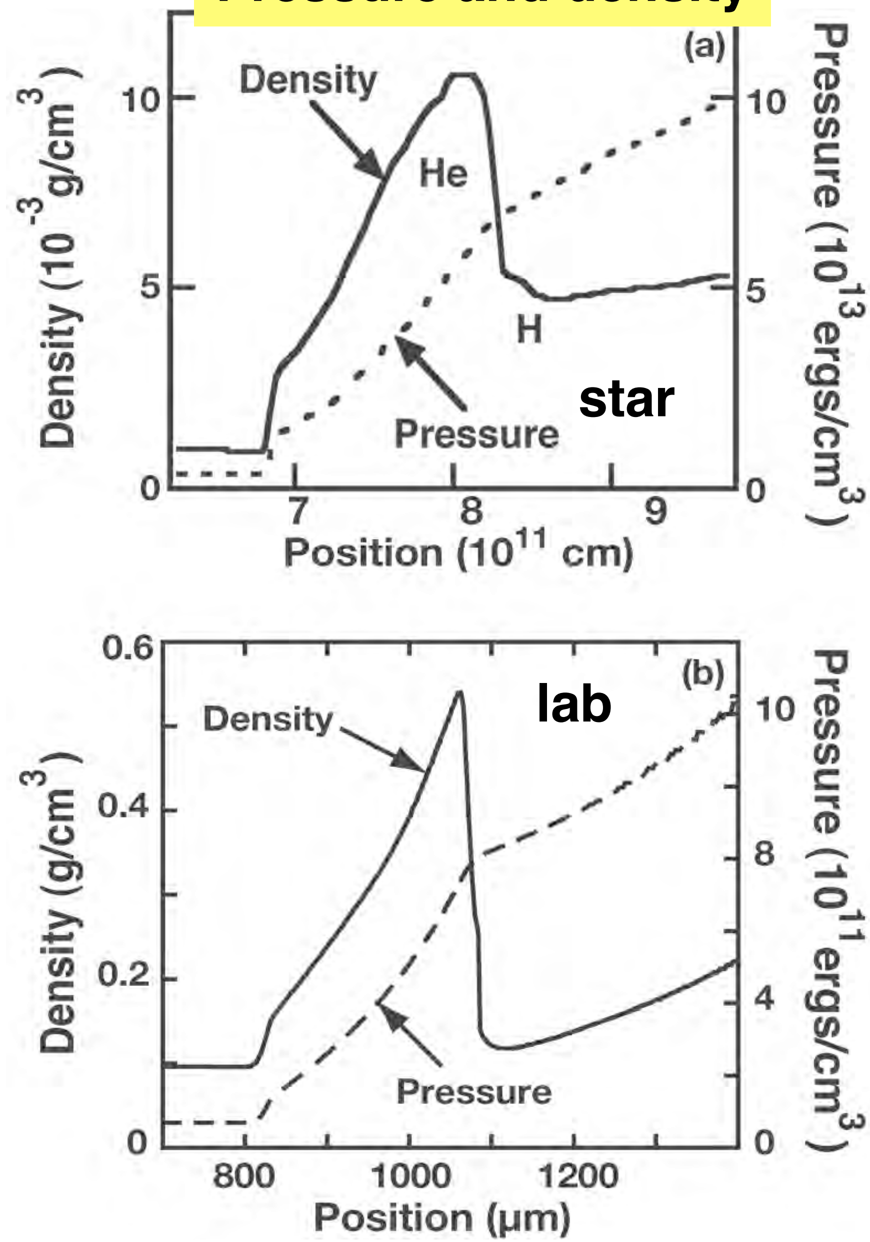
	SN	lab
h/λ_c	10^6	10^4
Re	2.6×10^{10}	1.9×10^6
Pe	1.5×10^{12}	1.8×10^3
$Pe\gamma$	2.6×10^5	…
τ_{BB}/τ	…	580

Boundary conditions in space and time must also be well-scaled

Interface velocity vs time



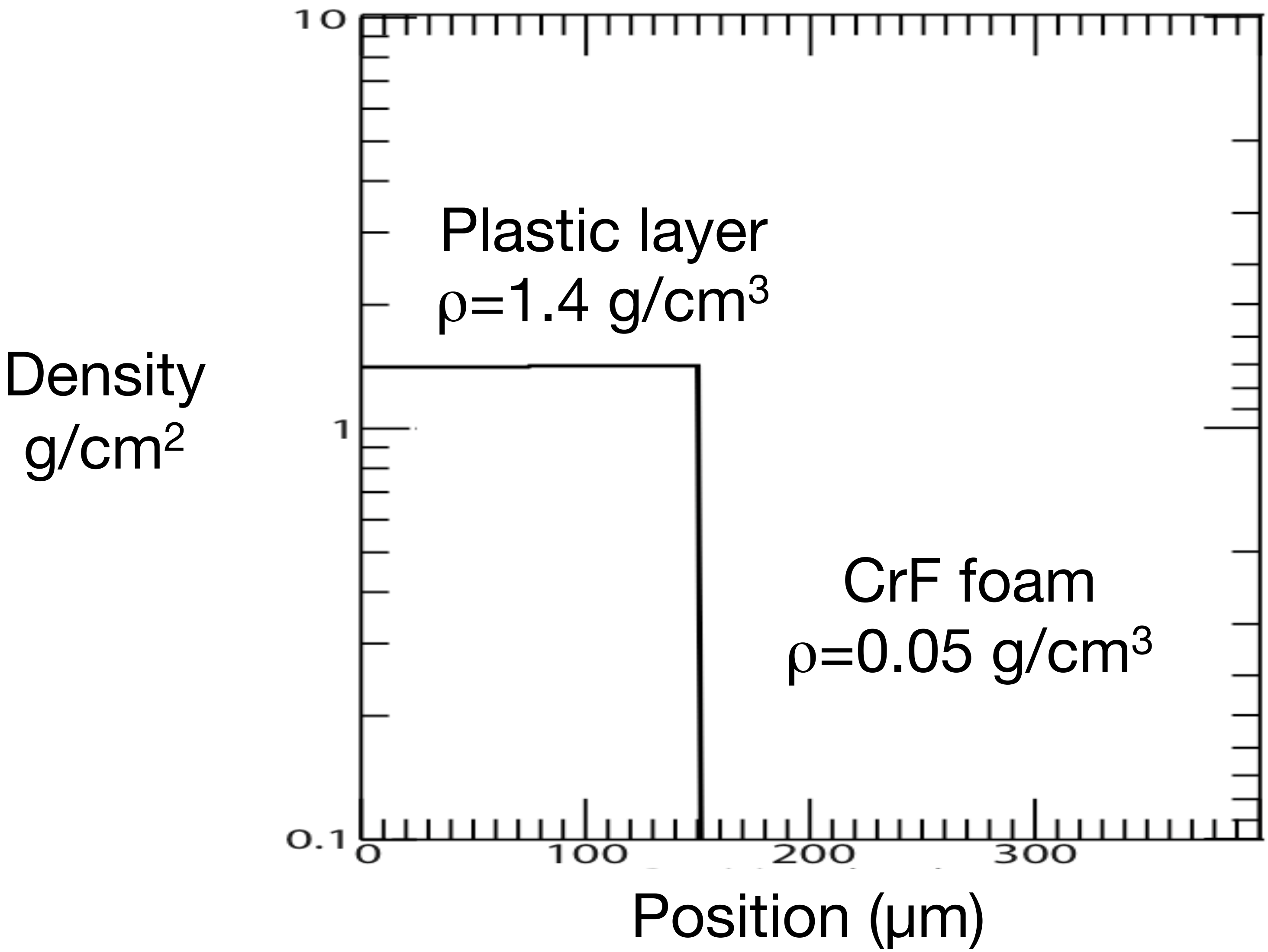
Pressure and density



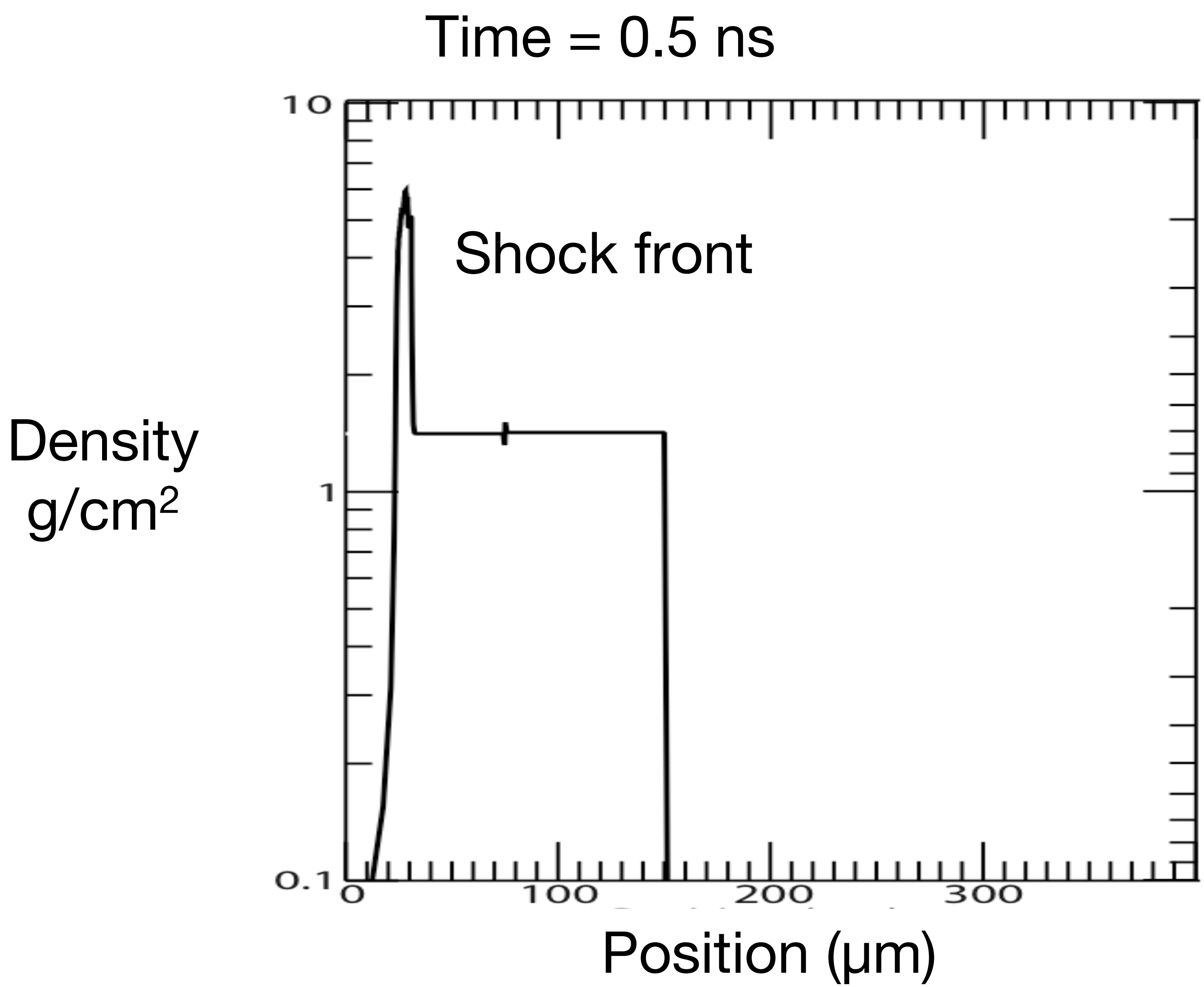
Planar Blast Wave Formation

- Shock wave created by ablation pressure from laser
- When laser pulse ends, expanding plasma causes a rarefaction wave
- Blast wave forms when rarefaction overtakes shock
- 1D simulation of experiment showing blast wave formation

HYADES Simulations of experiment

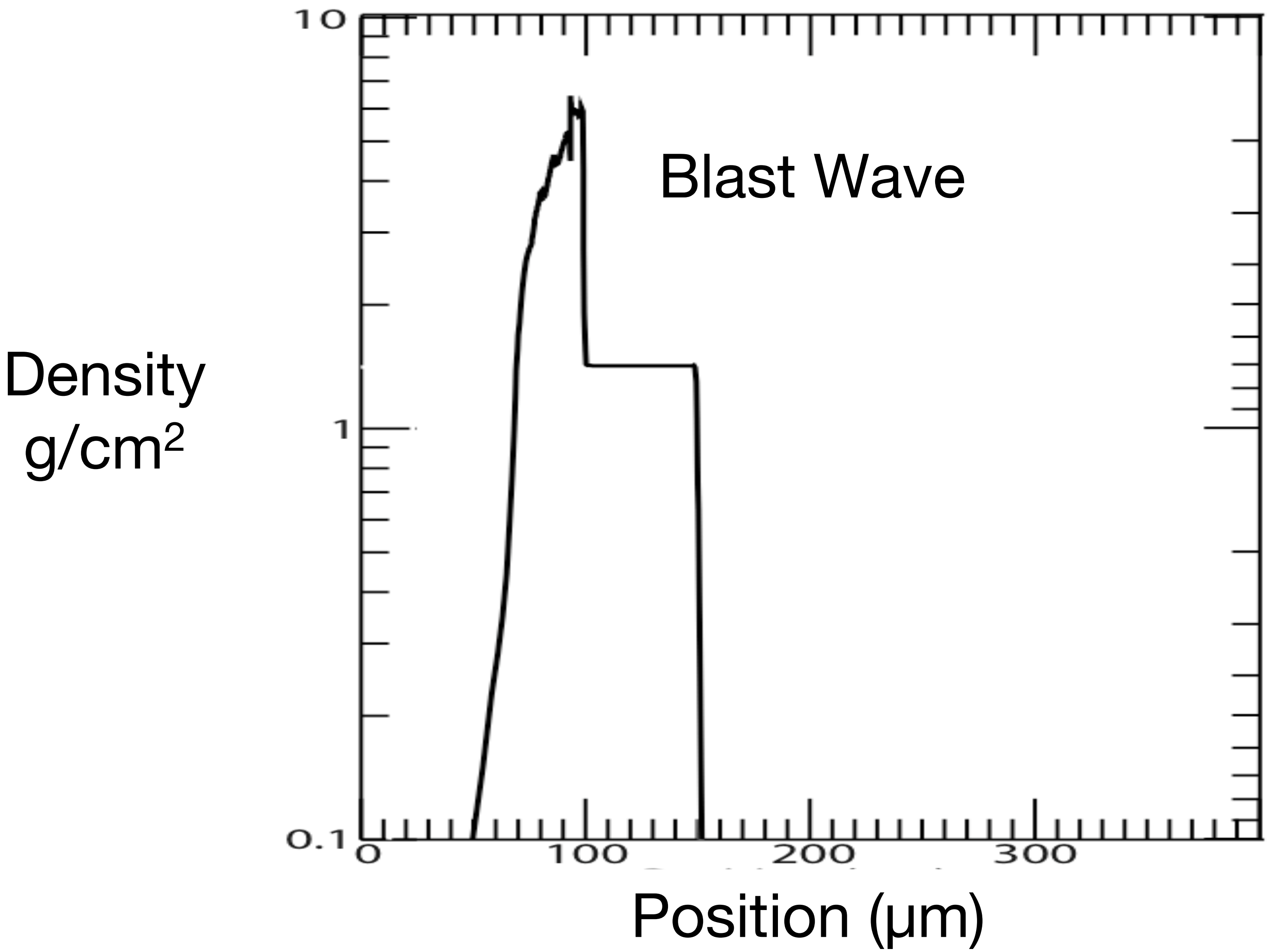


HYADES Simulations of experiment

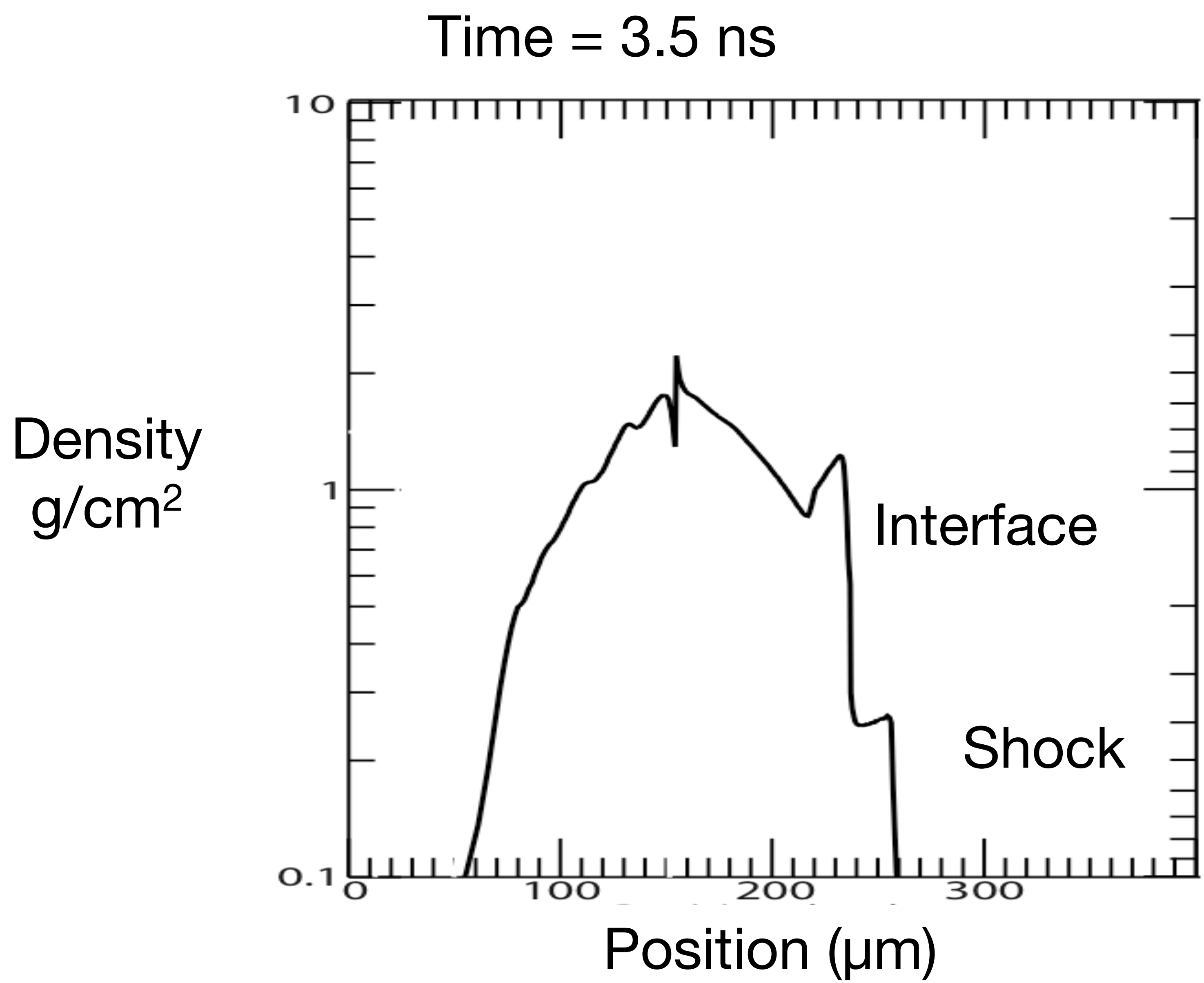


HYADES Simulations of experiment

Time = 1.5 ns

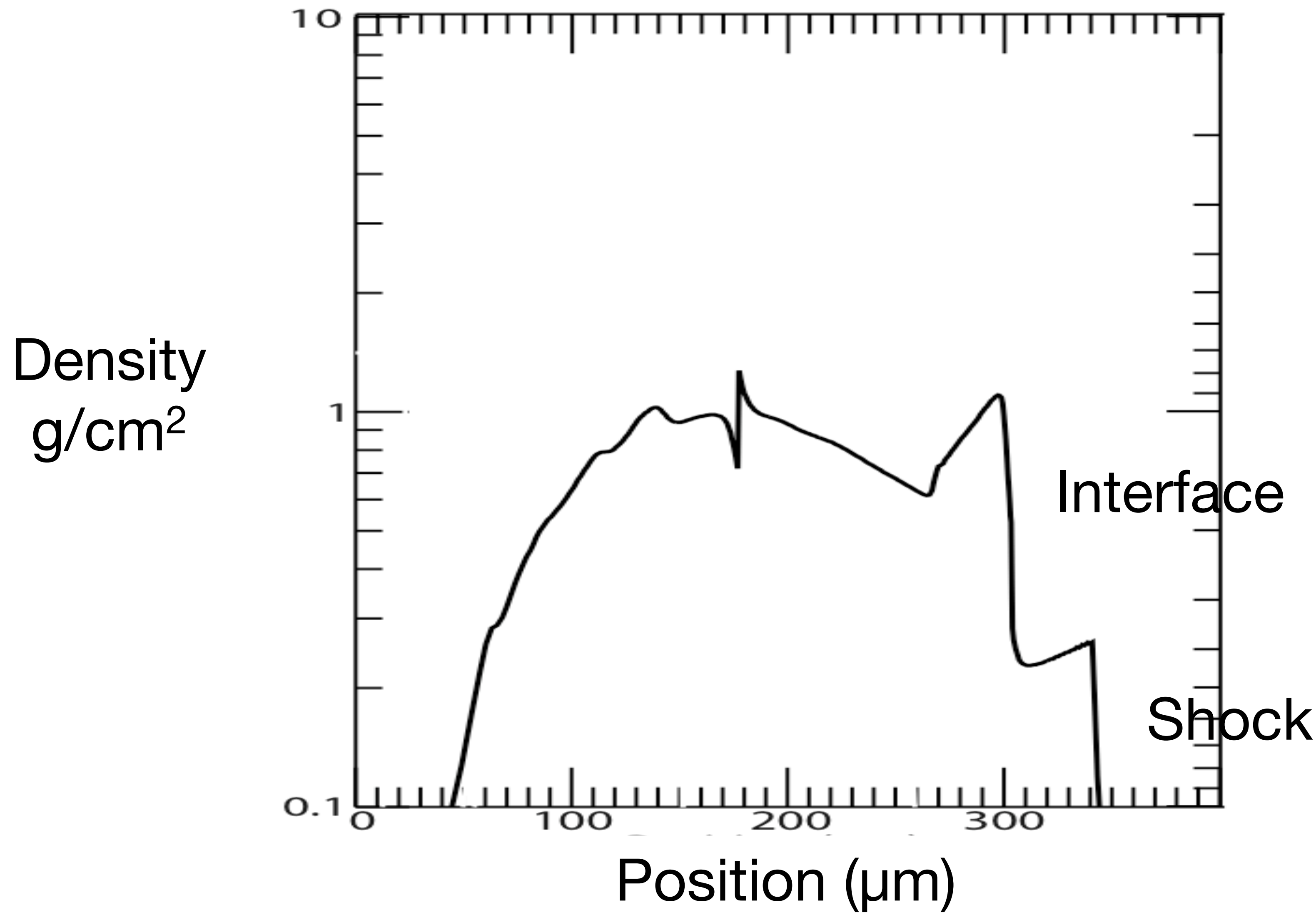


HYADES Simulations of experiment



HYADES Simulations of experiment

Time = 4.5 ns



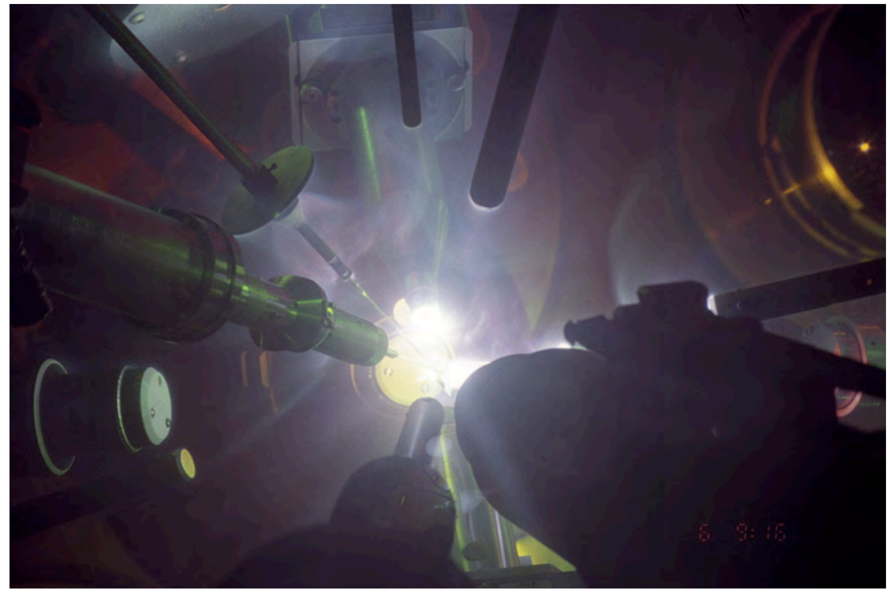
Acceleration of Interface Similar in SN1987A

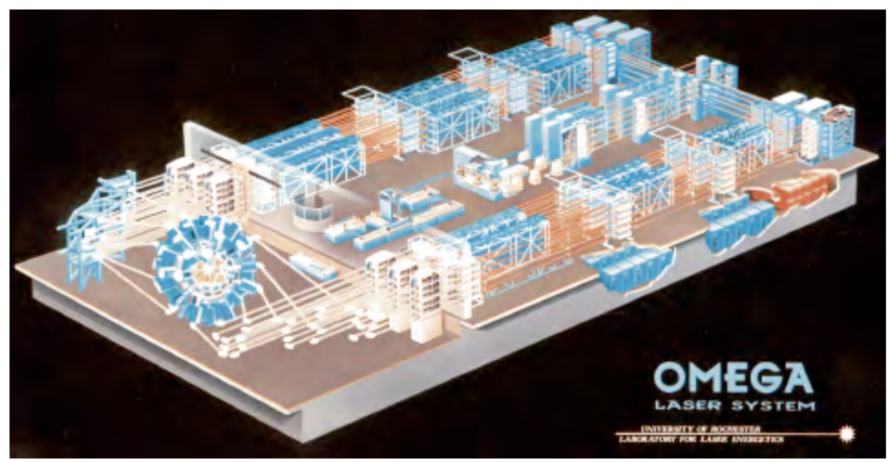
- Similar for SN1987A and experiment
- Density drop at interface creates hydrodynamic instabilities
  - Rayleigh-Taylor (RT)
  - Richtmeyer-Meshcov (RM)
- Experiment dominated by RT instability

Experimental Conditions at Omega Laser Facility

- Ten Omega Laser beams
  - ~500 J each, ~5 kJ total energy
  - λ = .35 μm, UV light
  - 1 ns square pulse
- Produce intensity of ~10^{15} W/cm^2
- Pressure of ~50 Mbars or 1 million atmospheres

Inside the Omega target chamber

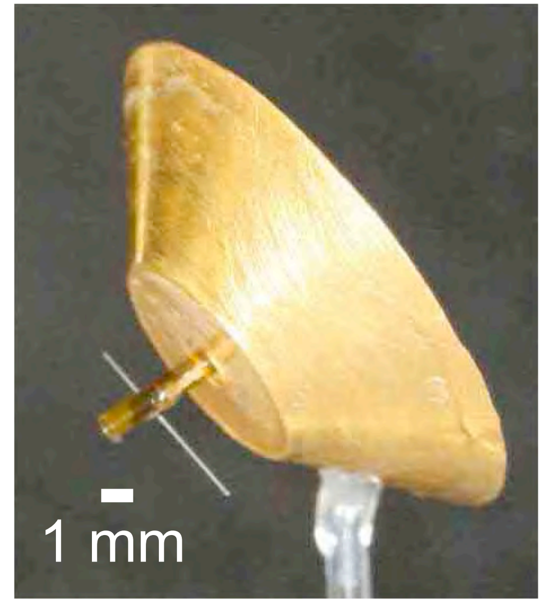




The Omega Laser System

Key components of target

- 150 µm plastic (1.41 g/cc)
  - made at General Atomics
  - Tracer strip material: $C_{500}H_{457}Br_{43}$ (1.42 g/cc)
- 2-3 mm Carbonized Resorcinol Formaldehyde (CRF) foam (50 mg/cc)
- Inside a polyimide shock tube



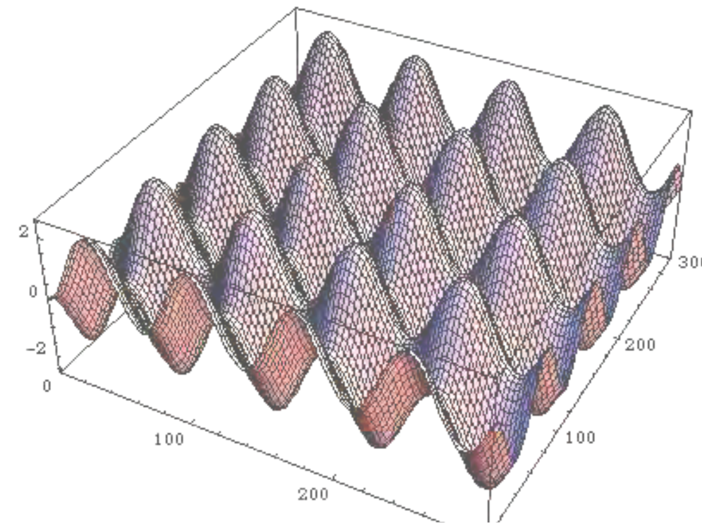
Target*

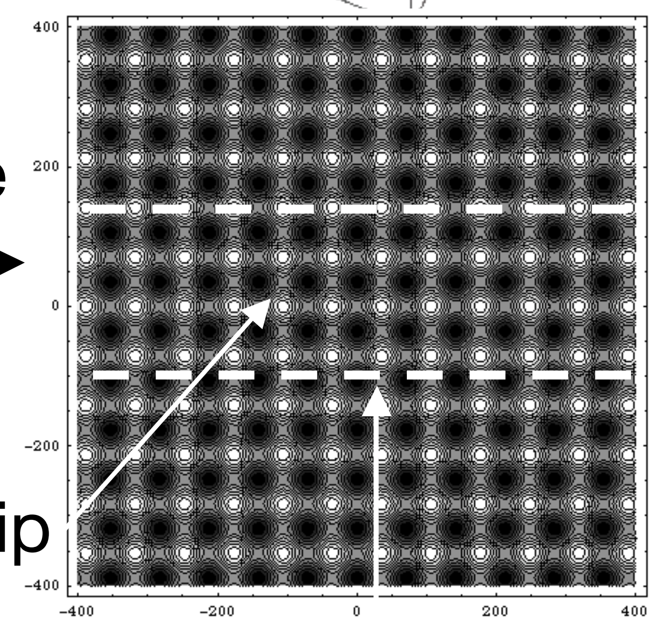
*Target Fabrication: M. Grosskopf, D. Marion, T. Donajkowski

Rayleigh-Taylor Seed Perturbations

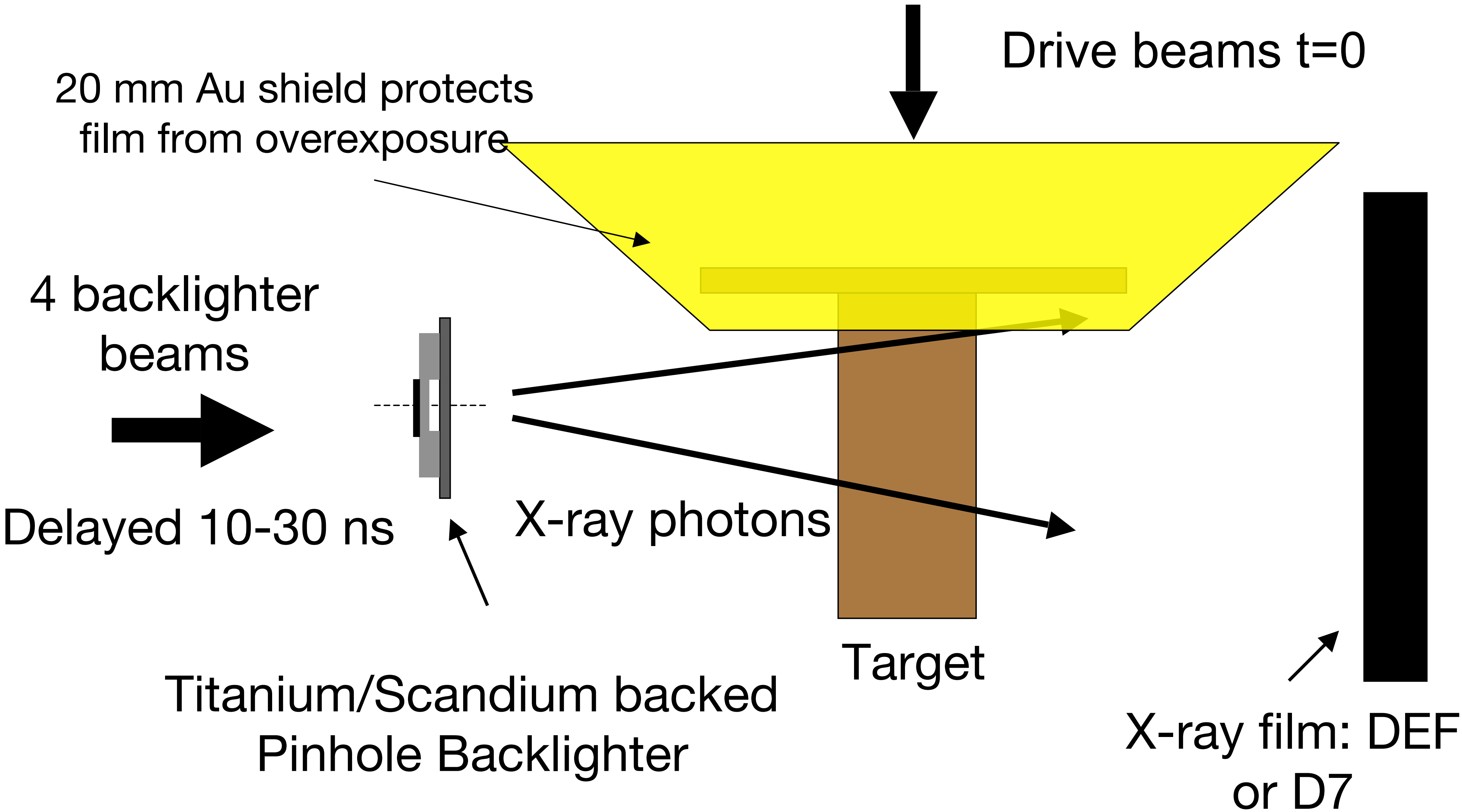
- Two sine waves in orthogonal directions creates “egg crate” pattern
- Single mode: a_o = 2.5 μm and $k_x = k_y = 2\pi/(71\ \mu m)$

Single mode

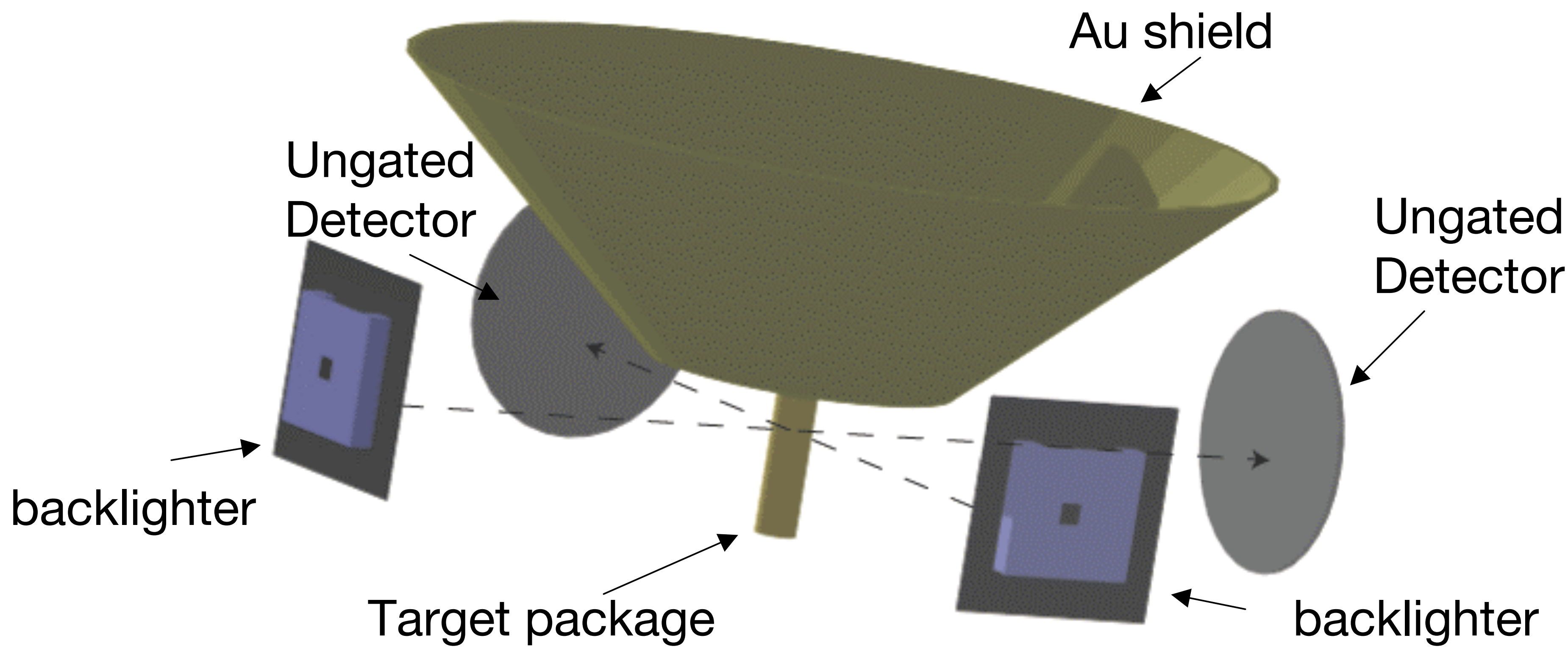




Diagnosing the Experiment

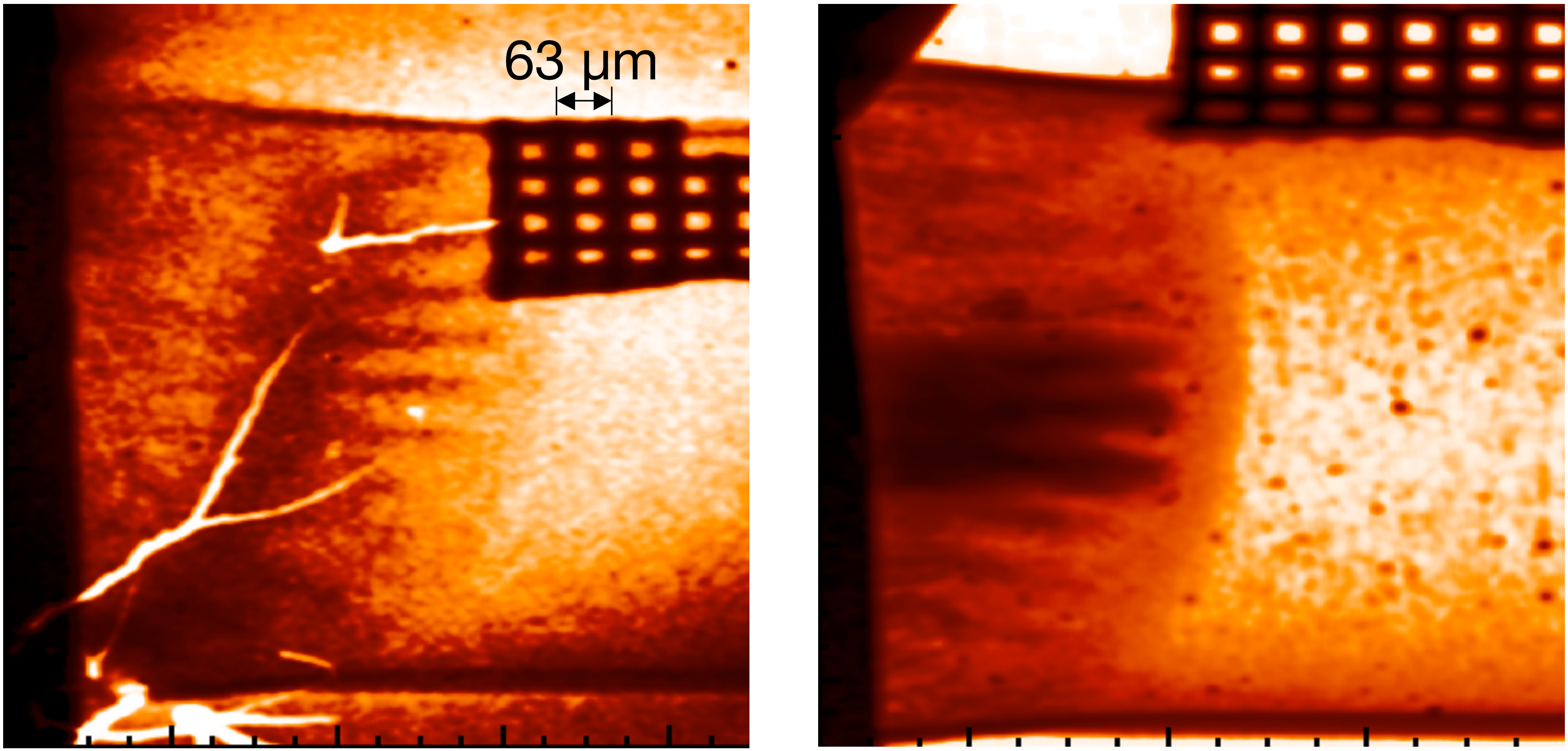


Target Design with Dual, Orthogonal Radiography



Aug 05: First Physics Data From Dual, Orthogonal, Simultaneous Radiography!

Single Mode Perturbation at 17 ns

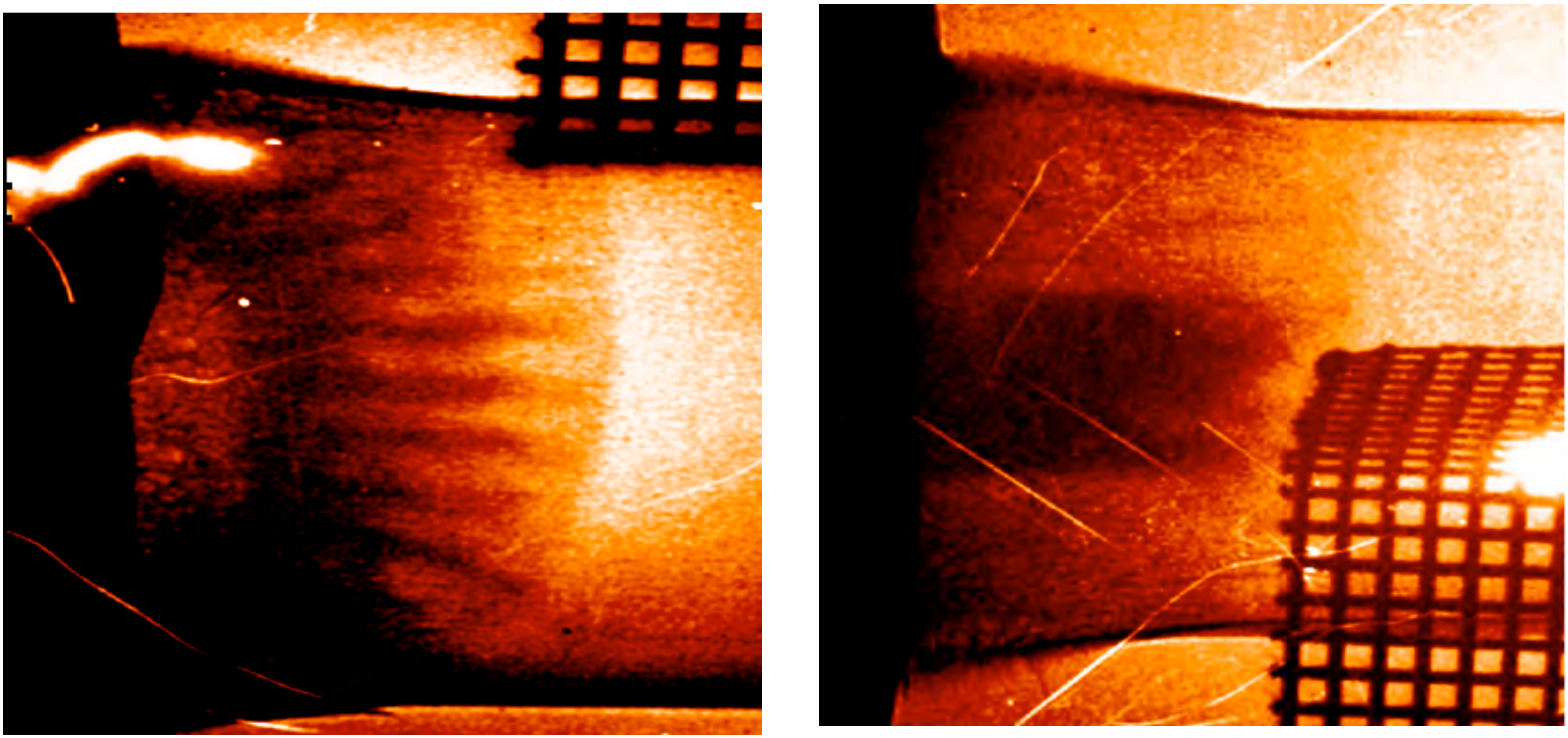


We have shown that the noise in these data is Poisson noise*

C.C. Kuranz et al., RSI, 2006

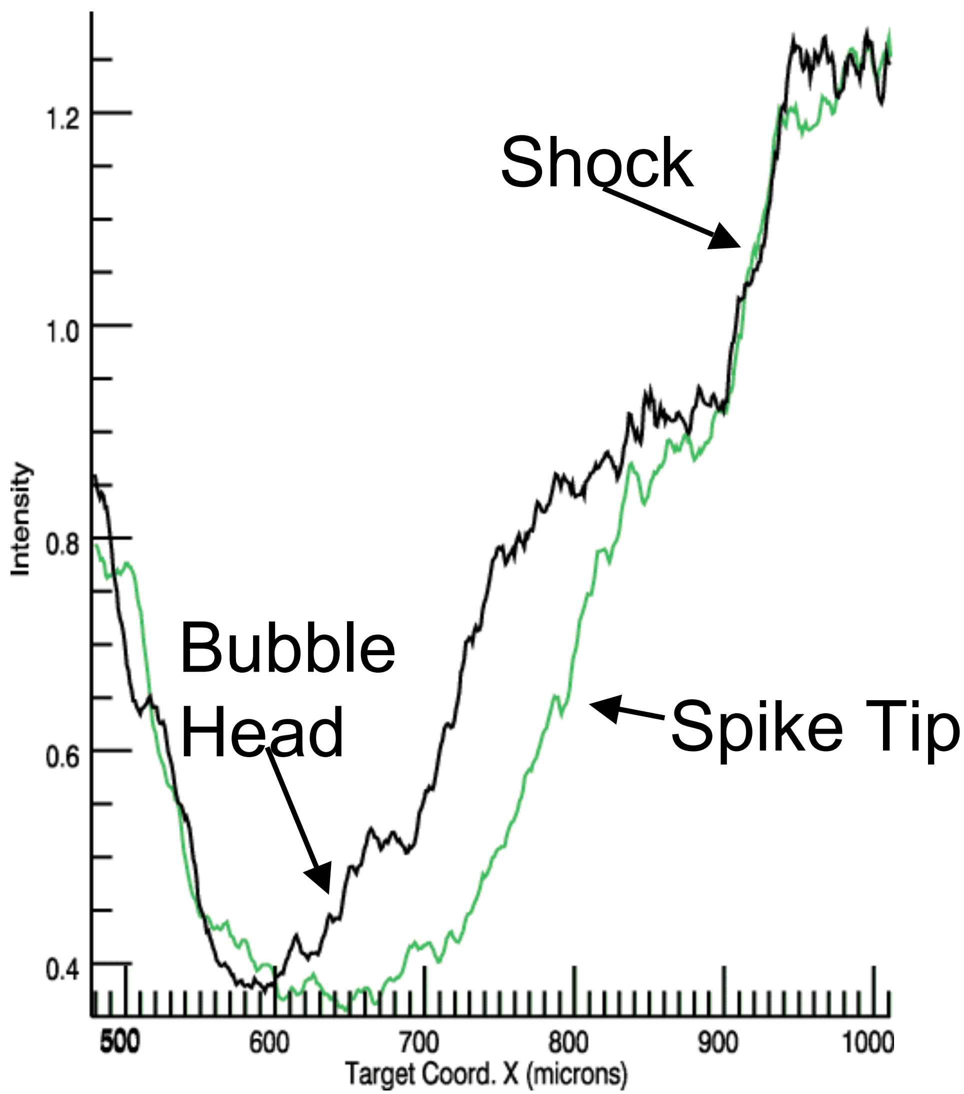
We completed our data set in December 2006

Single Mode Perturbation at 21 ns

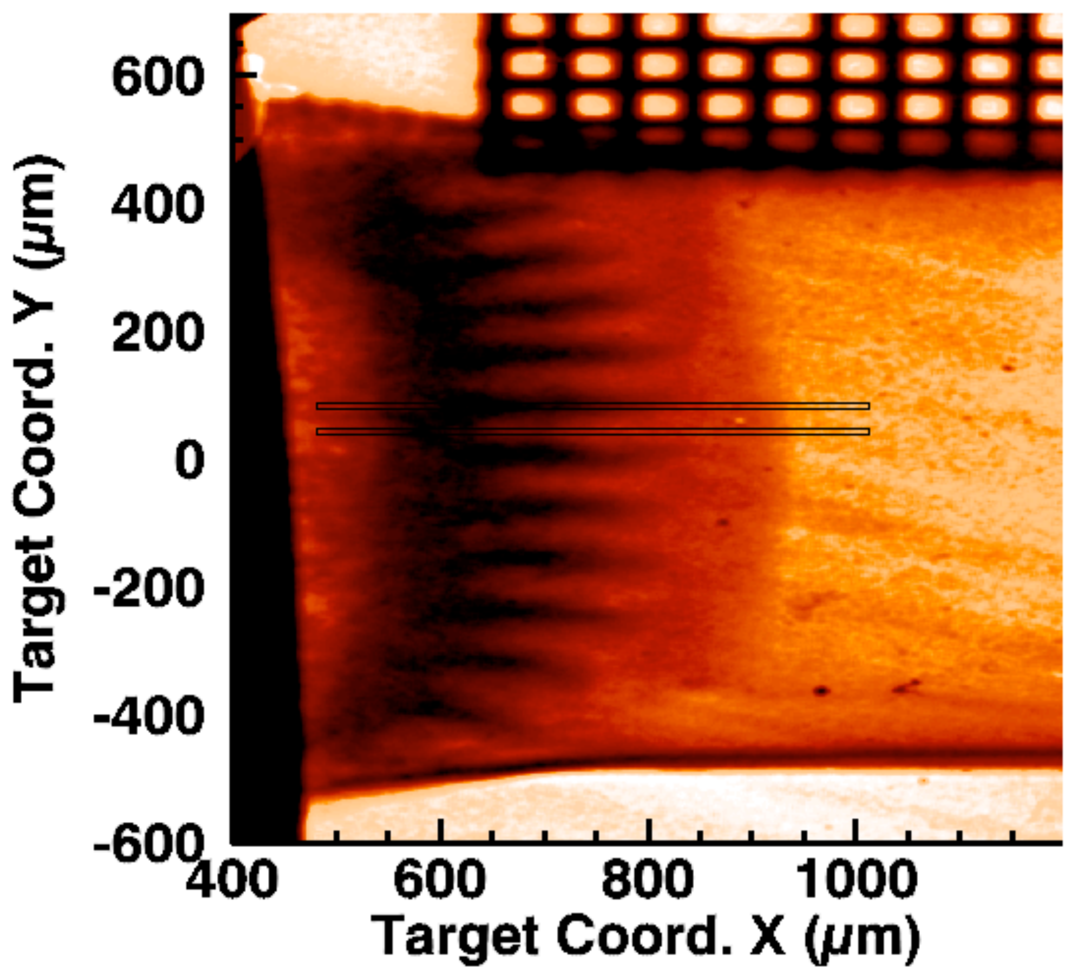


D7 film and smaller pinholes has greatly increased resolution

Data Analysis Method



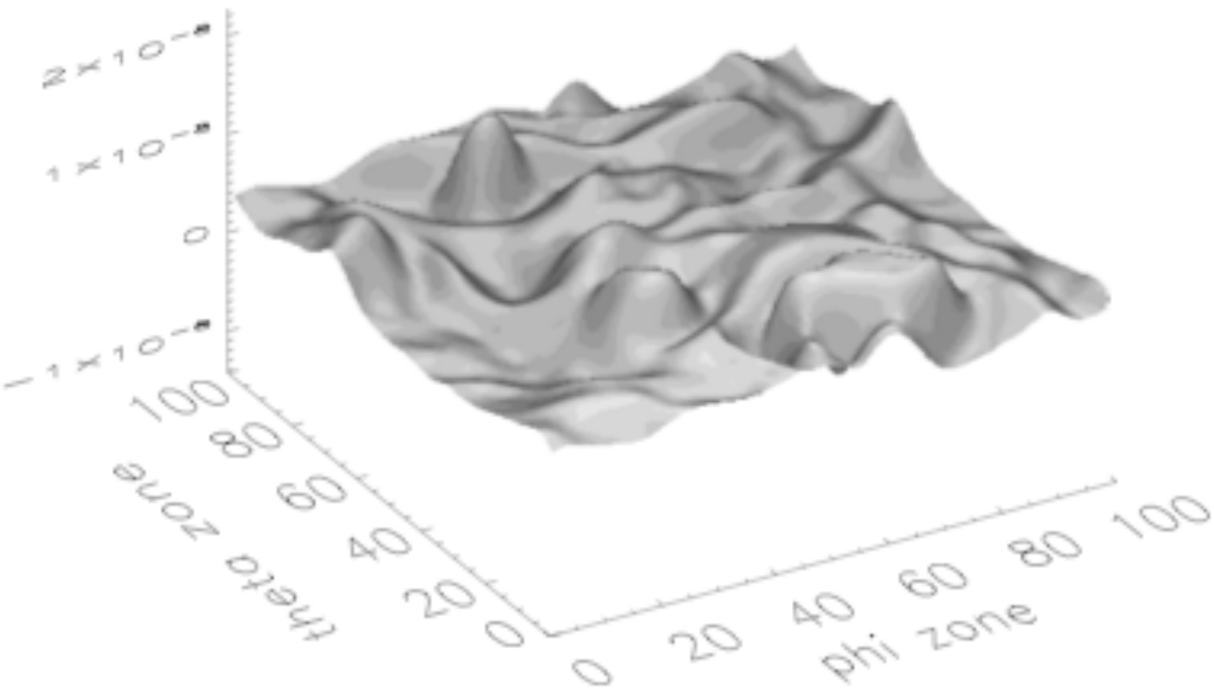
Data imaged at 17 ns



This analysis will let us address these issues

- RT growth rate
  - Corrected for the expansion of surrounding material
- Mass in spikes
- Differences between perturbation type
  - Growth rates
  - Structure
- Turbulent Regimes

Future of Experiment on Omega



- Aim for more realistic initial conditions
- Modeled hydrodynamics of pre-supernova stellar interior
- Interface distortion at convection boundary layer

*Simulations and image by Casey Meakin with Dave Arnett (U. of Arizona)

Machinability of Realistic Initial Conditions

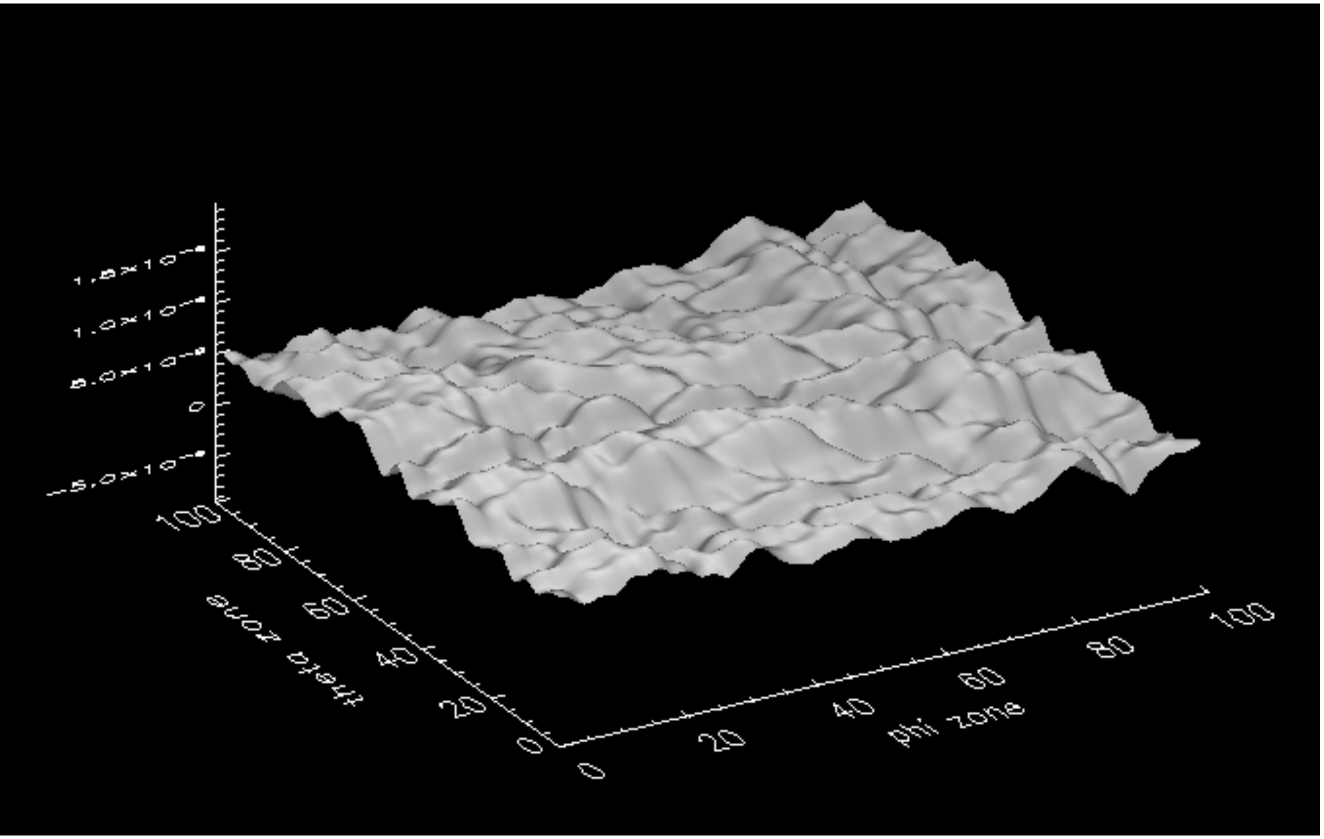
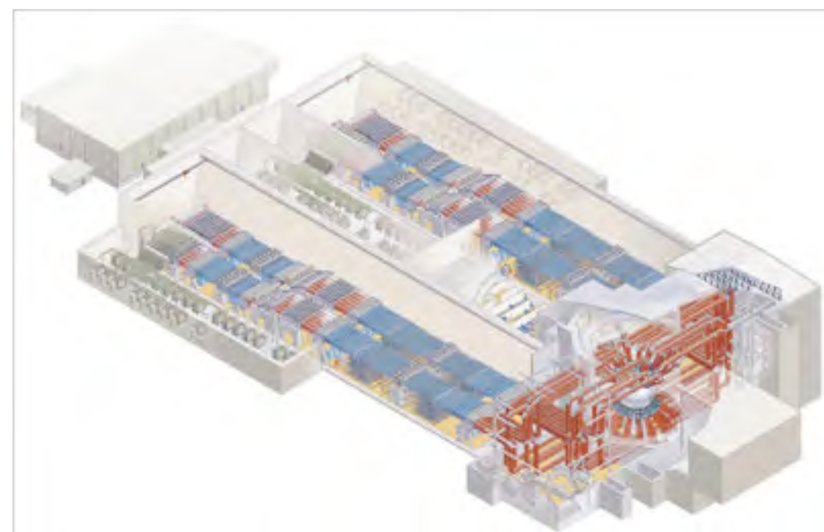


*Image by Forrest Doss

- Original design not currently machinable
- Reduced number of mode from over 10000 to ~50 while keeping same spectral shape

Prospects for experiments on NIF

- With the energy of NIF these types of experiments could explore…
  - Turbulence
  - Multilayer, spherically divergent experiments



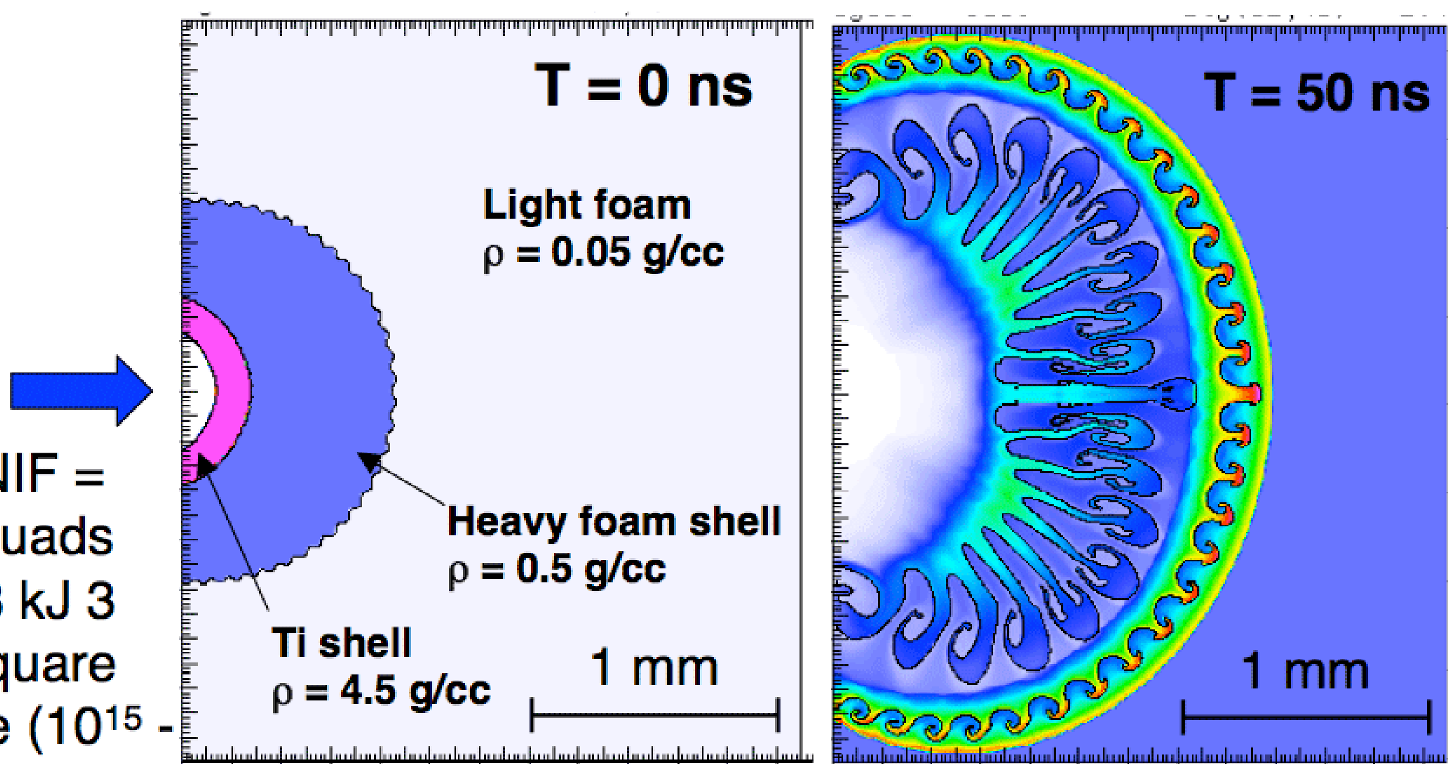
	NIF	Omega
# of Beams	192	60
Total Energy (kJ)	1800	40

Will SN hydrodynamics experiments go turbulent?

- Omega experiment does not appear to be turbulent
- Turbulence from spike tip interactions may or may not develop (Miles)
- RT growth and drive for turbulence dies away in experiment and in star
- Unclear to us how turbulent SN1987A should be
- NIF will allow for longer, larger acceleration to further explore these issues

Multiple interface, 3D spherically diverging SN experiments on NIF

1/2 NIF = 24 Quads ~288 kJ 3 ns square pulse (10^{15} - 10^{16} W/cm^2)



- Able to include (C+O)/He and Si/O interfaces as well as H/He interface

Conclusions and Future Directions

- We have successfully performed supernova hydrodynamics experiments on Omega
- We look forward to NIF for opportunities to explore these phenomenon further